An Advanced Technology for Structural Crashworthiness Analysis of a Ship Colliding with an Ice-Ridge: Numerical Modelling and Experiments

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Abstract

The structural engineering problem associated with a ship colliding with an ice-ridge involves highly nonlinear mechanisms including buckling, collapse, crushing, plasticity and fracture together with environmental and operational factors, such as the loading speed (strain rate), temperature and salinity. The objective of this paper is to develop an advanced technology for numerical computations of structural crashworthiness in the event of a ship colliding with an ice-ridge. The nonlinear finite element method is used for modelling the problem, in which the ship structures are modelled by plate-shell finite elements and the ice-ridge structures are modelled by solid elements together with the KOSORI ice material models. Two sets of experiments are performed to validate the numerical computations. In the first set of experiments, ice is dropped on a steel plate from a height of two meters, and in the second, a rigid body is dropped on a steel plate under the same conditions. The results of the two experiments are compared to determine the differences between the ice responses and rigid body responses on the steel plate. It is concluded that the developed technology is very useful for computing the structural crashworthiness of a ship when colliding with an ice-ridge. Details of the test results are documented.

Keywords: Structural crashworthiness, collisions between ships and ice-ridges, impact engineering, fracture, plasticity

1. Introduction

In the Arctic region, ships and offshore structures are increasingly being exposed to the impact loads arising from collisions with ice ridges and floating in ice infested waters. Thus, predicting the ice loads has become a necessary parameter in the structural design of ships and other marine structures. An ice ridge-marine structure collision event can be characterised by the external and internal mechanics, as shown in Figure 1 [1].

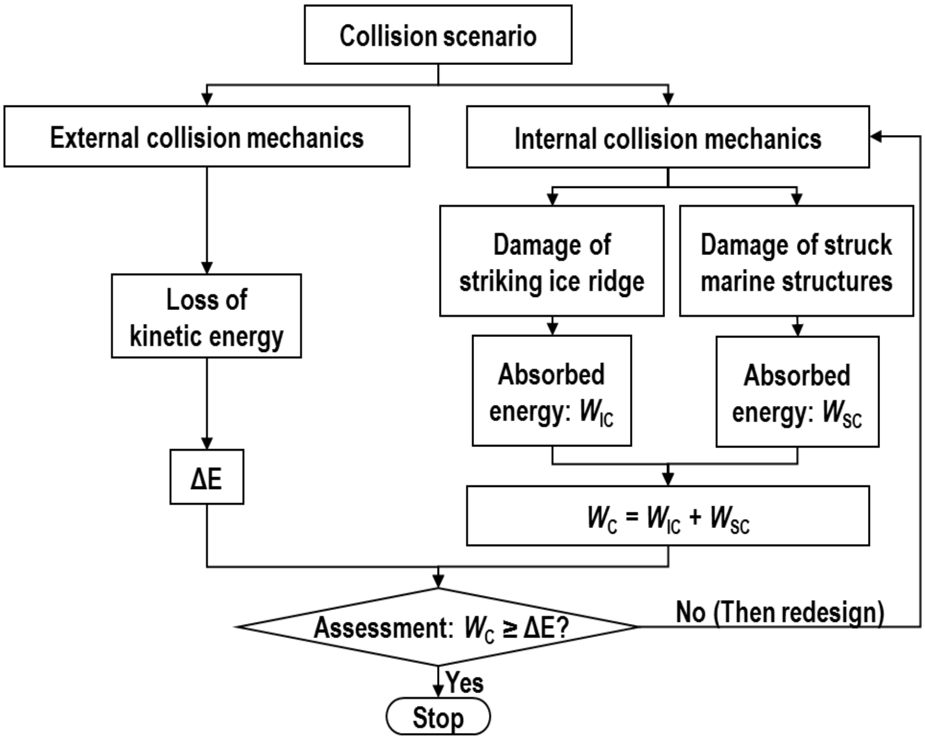


Figure 1 Representation of the analysis procedure for an ice ridge and marine structure collision event

The internal mechanics relate to the energy absorbed by the colliding bodies in terms of the damage they incur. In some studies, the ice is assumed to act as a rigid material in a collision [2], and thus, all of the collision energy is absorbed by the steel structure. In reality, however, steel is much stronger than ice and the collision energy is shared by both colliding bodies. This approximation is referred to as the shared energy method and is indicated in Figure 2. The material models of both the steel and ice materials should be characterised in numerical computations because the collision impact energy is dissipated in the deformation of the colliding bodies.

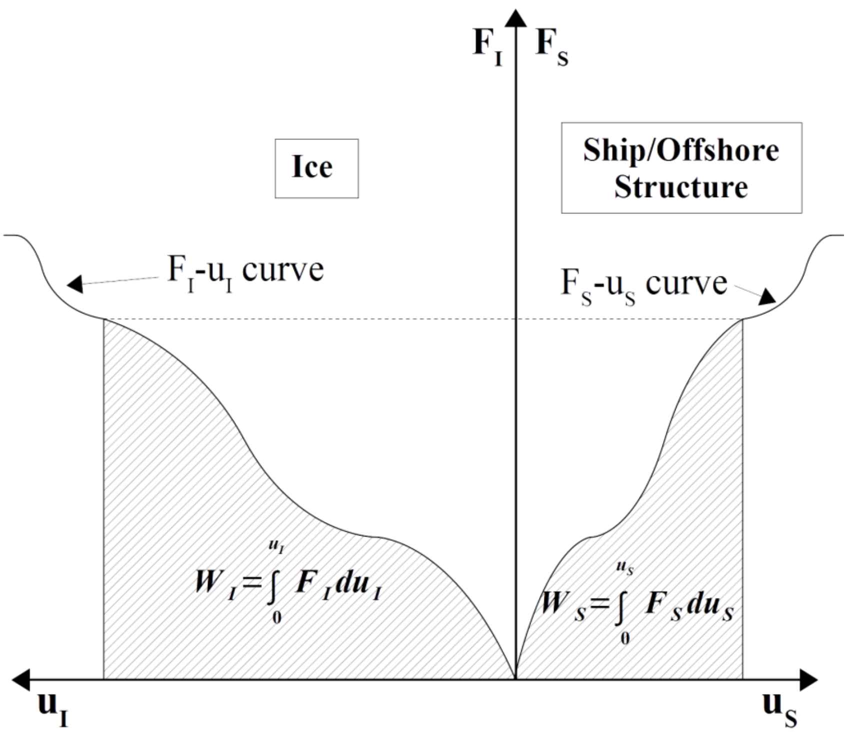


Figure 2 Energy components absorbed by ice and the marine structure

Ince et al. [3] developed the so-called KOSORI ice model, which includes a constitutive equation and a fracture model of the ice structural mechanics. This comprehensive model incorporates the effects of influencing parameters, such as the strain rate, temperature and salinity, based on experimental results.

The motivation of this paper comes from the need to validate the model. In this paper, the ice strength and fracture behaviour in the KOSORI ice model are combined with the traditional metal strength model to implement as a user defined material model (UMAT) in a nonlinear finite element program to solve the ice-steel interaction problem. An experiment is conducted on the interaction between a steel plate and ice to validate the developed methods. In addition, a rigid body drop test is performed in similar conditions to the ice drop test to show the difference between considering ice as rigid and as deformable.

2. Experiments

There is a lack of experimental evidence on the impact between ice and steel, with only a few numerical and experimental studies [4–6] in the literature. Two main approaches are used to model the impact between ice and steel. First, all of the energy is absorbed by the steel and second, the energy is absorbed by both the ice and the steel structure. The experiments presented in this paper were performed to understand the interaction between ice and steel under impact loading conditions. Two different types of experiments were conducted.

- Rigid indenter: a rigid cone-shaped indenter was dropped on a steel plate with a specific impact velocity. This was performed to understand and compare the behaviour of the steel in the ice impact and rigid impact conditions.
- Ice indenter: a cone-shaped indenter made of fresh water ice was dropped on a steel plate to understand the shared energy approach for simulating the interaction between ice and steel.

Figure 3 shows the set-up of the experiment, which consists of an indenter whose falling direction is controlled by guidelines at the sides. A high-speed camera is used to capture the fracture propagation in the ice and a load cell with a capacity of 1000 kN is used to obtain the force changes with a high accuracy with respect to time.

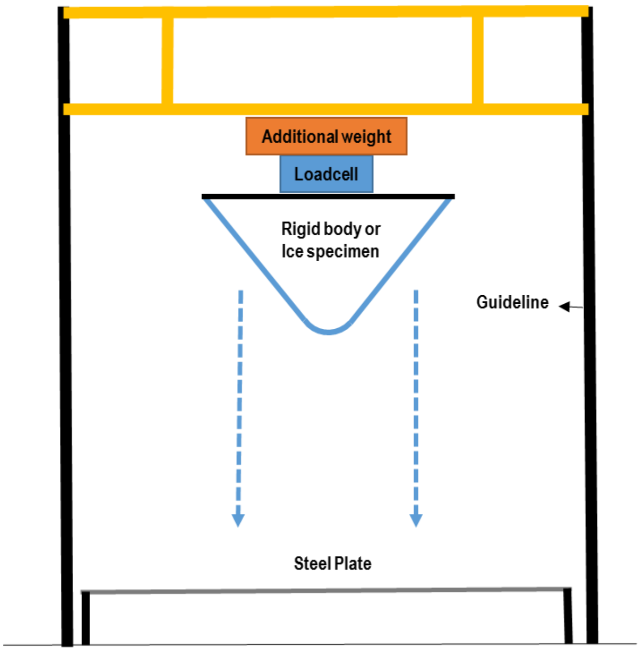


Figure 3 Schematic diagram of the drop test setup

2.1 Rigid body drop test

A conical rigid indenter (760 kg) was dropped on a mild steel plate (1.2m×1.2m×2.9mm) from a height of two meters at a right angle. The steel plate was bolted to a rigid holder to avoid welding distortion. The details of the experiment details are summarised in Table 1 and Figure 4, which shows the cone-shape indenter and the dimensions. Figure 5 illustrates the test set–up.

Table 1 Details of the rigid body drop test experiment

Exp. No.	Interaction Type	Total Weight	Height
1	Rigid – steel	760 kg	2 m

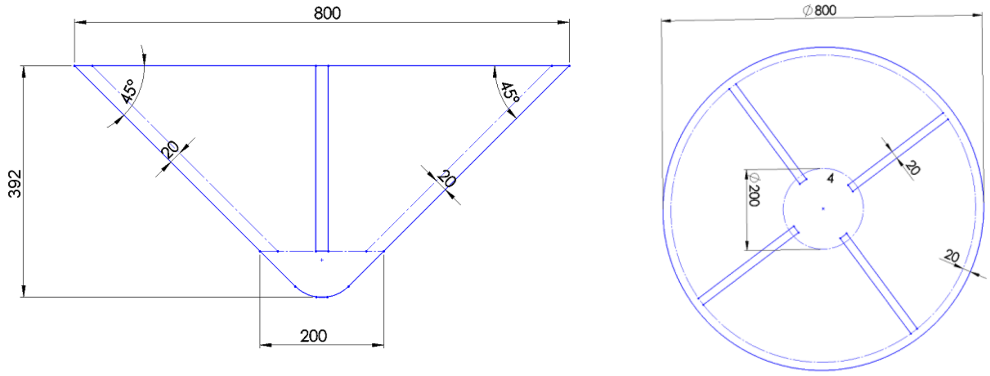


Figure 4 Dimensions of the cone-shaped dropped object

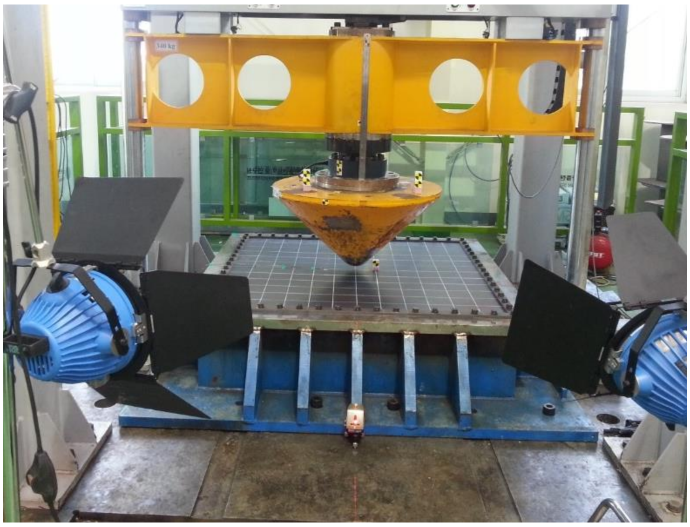


Figure 5 Set-up of the rigid body drop test experiment

2.2 Ice drop test

An ice drop test was conducted to understand the ice-steel interaction. The ice indenter weighed 830 kg, including the holder, and a 126.5 kg ice mass was dropped from a 2 m height. Table 2 provides the details of the ice drop experiment.

Table 2 Details of the ice drop test experiment

Exp. No.	Interaction Type	Ice Weight	Total Weight	Height
2	Ice – steel	126.5 kg	830 kg	2 m

The most important part was to make the ice for conducting the experiments. The ice was prepared in a very particular way to homogenise the crystalline structure in the cone shaped mould. The ice mould was prepared with the same dimensions as the cone-shaped rigid indenter, whose dimensions are given in Figure 4. Ice cubes were used to make the ice indenter. First, the ice cubes were crushed and mixed with 0^{o}C water to maintain the uniformity of the crystalline structure during freezing and were frozen for 24 hours. When completely frozen, the ice indenter was tightly mounted with rubber bands on the test setup. Figure 6 shows the ice making process.

Figure 6 Ice preparation process

The experiment was recorded with a high-speed camera to observe the propagation of the fracturing in the ice. The test set-up is shown in Figure 7. The experiment was performed in a short time at room temperature to avoid melting during the experiment.

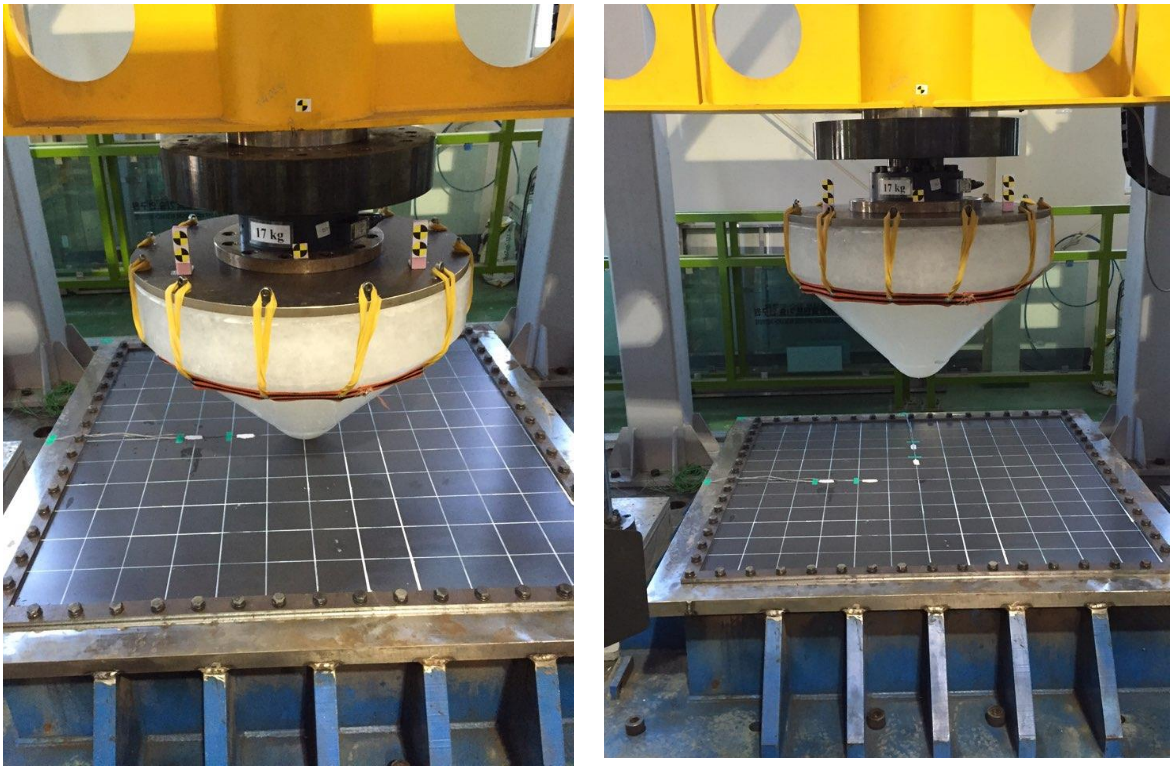


Figure 7 Test set-up for the ice drop test

3. Numerical Model

Numerical computations are the easiest and most economical way to understand material responses without conducting experiments. However, it is necessary to use material models with well-defined properties for both colliding bodies. In this section, the material models of steel and ice are examined.

3.1 Steel material model

Steel is a durable and robust material that is widely used in various engineering sectors, such as civil engineering, ship engineering, and aircraft and space engineering. Although it has some non-linearities, there are good numerical models in the standard library of finite element programs that can solve the structural mechanical problems of steel numerically and empirically. The piecewise linear plastic model with the Cowper-Symonds relation is the most suitable for our problem. The Cowper-Symonds equation is the most well-known model for describing the material behaviour at different strain rates. Table 3 shows the Cowper-Symonds coefficients for mild and high tensile steel and Figure 8 compares the model and experiments. The Cowper-Symonds model has been successively applied in studies of ship to ship collisions [7–9].

Table 3 Cowper-Symonds coefficients for mild and high tensile steel

Material	C [s^{-1}]	q	Reference
Mild Steel	40.4	5	Cowper&Symonds (1957)
High Tensile Steel	3200	5	Paik et. al. (1999)

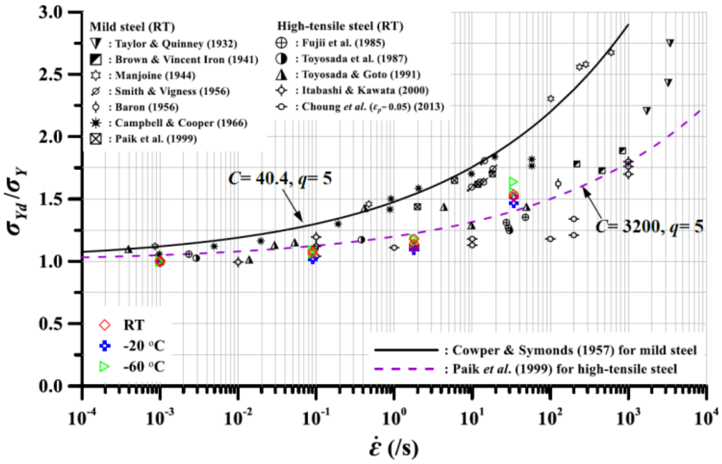


Figure 8 Dynamic yield strength plotted against the strain rates for mild and high tensile steel [1,10].

The Cowper-Symonds equation is shown in Eq. 1, and the coefficients of the mild steel numerical model are indicated in Table 4.

$$\frac{\sigma_{Yd}}{\sigma_Y} = 1.0 + \left(\frac{\dot{\varepsilon}}{C}\right)^{1/q} \tag{1}$$

Table 4 Plate material properties.

Parameter	Value
Elasticity modulus	210 000 [MPa]
Poisson Ratio	0.3
Yield Stress	268 [MPa]
Fracture Strain	0.35
C	40.4
q	5

3.2 Ice material model

To solve the steel-ice interaction, it is necessary to create an accurate ice model that produces comparable results to the experimental and numerical simulations. Therefore, the KOSORI ice model, which was proposed by Ince et. al. (2016), is implemented in the finite element program as a subroutine for ice material modelling. The model has two parts: the constitutive relationships and fracture mechanics of ice.

3.2.1 Constitutive model of ice

The constitutive relationships of the KOSORI ice model are indicated in Eq. 2, which considers the effects of the strain rate, temperature and salinity on the ice material:

$$\sigma = A\left[1 + B\ln\left(\frac{\dot{\varepsilon}}{\dot{\varepsilon}_o}\right)\right]\left[C\left(\frac{T}{T_o}\right)\right]\left[D\ln\left(\sqrt{\frac{v_b}{v_{bo}}}\right)\right] \quad \text{[MPa]} \tag{2}$$

where A, B, C and D are coefficients, $\dot{\varepsilon}$ is the strain rate, T is the temperature and $\sqrt{v_b}$ is the root brine volume reference parameters. The coefficients for Eq. 2 are given in Tables 5 and 6.

Table 5 Reference parameters for the ice model

Reference	**Parameters**
$\dot{\varepsilon}_o$	10^{-2}
T_o	-10°C
$\sqrt{v_{bo}}$	0.5

Table 6 Ice material coefficients for the KOSORI ice model

	Ductile ([10^{-5}, 10^{-2}] strain rate)		**Brittle (After 10^{-2} strain rate)**	
A	11.74	[MPa]	3.64	[MPa]
B	0.08		0.37	
C	0.8		0.8	
D	-0.4		-0.4	

The constitutive equation is implemented in the Ls-Dyna program using the user defined material model (UMAT), which is a modified Johnson-Cook material model. Therefore, a similar methodology to the Johnson-Cook material model is used for the constitutive equation. Figure 9 shows the implementation procedure for the constitutive equations.

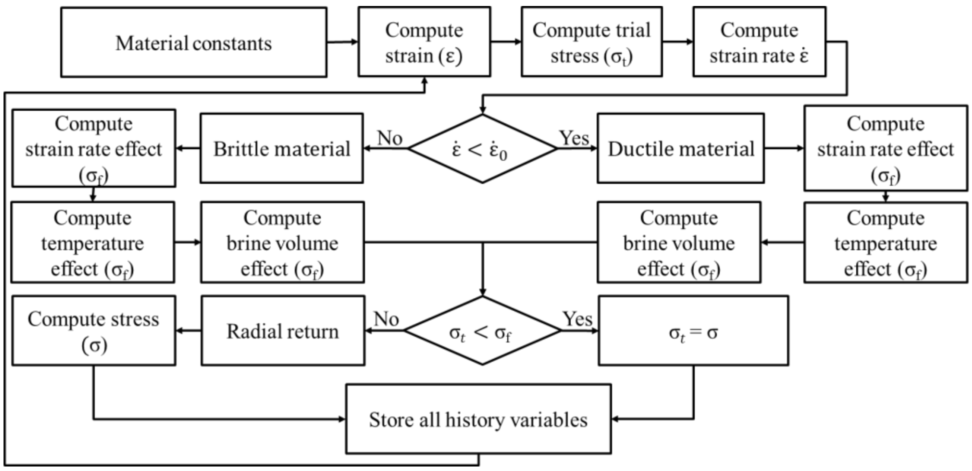


Figure 9 Implementation procedure of the constitutive equations of ice

3.2.2 Fracture model of ice

A cohesive zone approach is suggested for simulating fractures in the KOSORI ice model. In this model, brittle and ductile behaviour is defined by using the traction separation law and the strain rate dependency of the fracture toughness is defined by the depended energy release rate. Figure 10 shows the changes in the fracture toughness by the strain rate for ice.

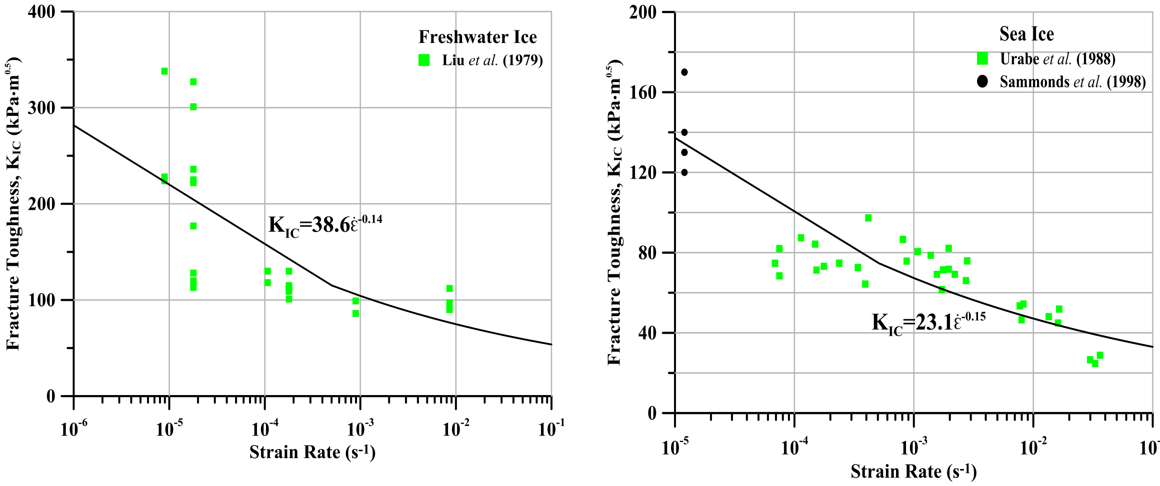


Figure 10 Changes in the fracture toughness by the strain rate for fresh water and sea water ice

The following equation gives the energy release rate and the fracture toughness relationship:

$$G = K^2(1-\nu^2)/E \tag{3}$$

where G is the energy release rate, K is the fracture toughness, ν is the Poisson ratio and E is the elasticity modulus.

The cohesive zone element method is a phenomenological model in which a zero thickness element is modelled between bulk elements. The element energy is calculated using the traction separation relations. When an element reaches a certain level of energy, the element is deleted and the bulk elements separate. Cohesive elements are not real elements, so the strain rate dependency cannot be implemented directly in the model. The strain rate dependency of the energy release rate should convert to the fracture opening speed relationship. Eq. 4 gives the relationship between the dynamic strain energy release rate and the fracture opening speed.

$$G_d = G_0\left[5 - \alpha\, ln\left(\dot{\delta}_m\right)\right] \quad \text{[N/mm]} \tag{4}$$

where G_d is the dynamic strain energy release rate, α is the coefficient, G_0 is the reference energy release rate and $\dot{\delta}_m\ is\ \dot{\delta}/\ \dot{\delta}_0$ is the fracture opening speed.

The Tvergaard and Hutchinson (1992) traction separation model is used in the KOSORI ice model. To define the change from ductile to brittle behaviour, the curve moves from a trapezoidal to a triangular shape (Figure 11) depending on the fracture opening speed. The other parameters of the curve are calculated using Eq. 5.

$$\delta_C = \frac{G}{A_{TSLC}\sigma_{max}} \quad (5)$$

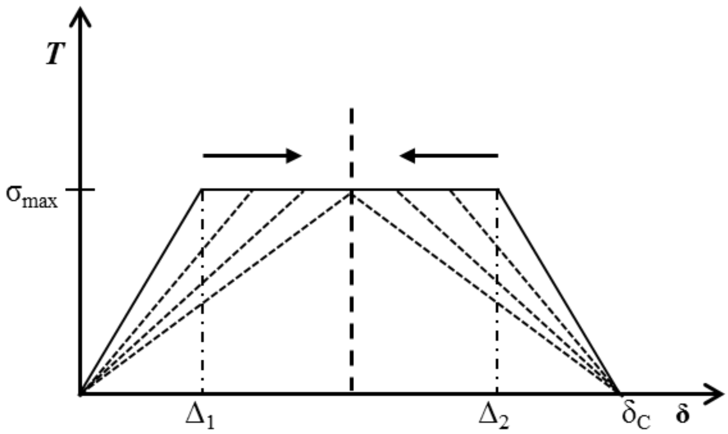


Figure 11 Traction-separation curve for the ice model

The traction-separation curve changes are formulated as defined in Eq. 6.

$$\frac{\Delta_1}{\delta_c} = \begin{cases} 0.1 & for \quad \ln(\dot{\delta}_m)/\beta < 0.1 \\ \ln(\dot{\delta}_m)/\beta & for \quad \ln(\dot{\delta}_m)/\beta > 0.1 \\ 0.5 & for \quad \ln(\dot{\delta}_m)/\beta > 0.5 \end{cases} \quad (6)$$

Table 7 shows the parameters and coefficients found using equations 5 and 6.

Table 7 Ice fracture model coefficients

Coefficients	
A	20
B	5

Table 8 The reference CZM parameters for ice

Energy Release rate	G_0	0.05 N/mm
Traction separation curve coefficient	Δ_1	0.1
Density	Ρ	0.9 g/cm^3
Maximum traction	T	10 MPa

The model is implemented in the Ls-Dyna explicit finite element program using the user defined model. Figure 12 shows the implementation procedure of the model.

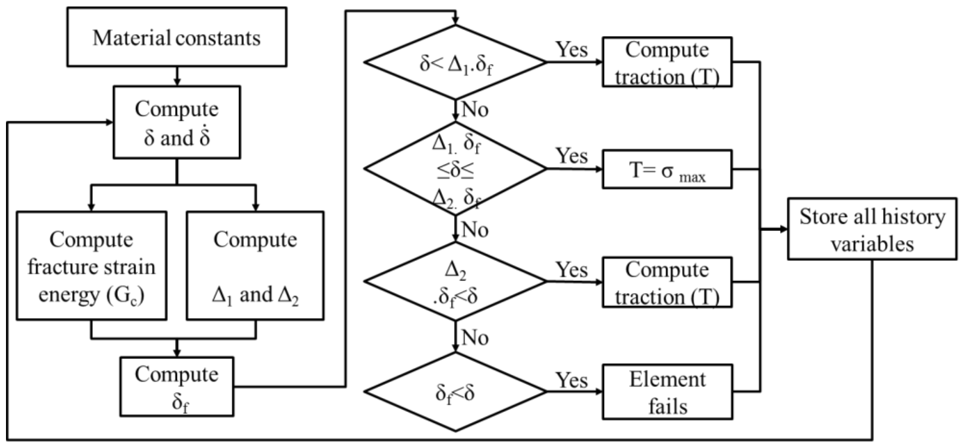


Figure 12 Implementation procedure for the ice fracture model

3.3 Analysis

The material models are defined as described in the previous section. The additional parameters for the ice material are shown in Table 9. The experimental set-up is incorporated in a computer program as shown in Table 10.

Table 9 Ice material properties

Density	Poisson's ratio	Young's modulus
900 kg/m3	0.3	9800 MPa

Table 10 Summary of the experiments and analysis details

Interaction Type	Total weight	Drop Height	Plate material	Plate thickness
Rigid-steel	760 kg	2 meter	Mild Steel	2.9 mm
Ice-Steel	830 kg (126.5kg ice)	2 meter	Mild Steel	2.9 mm

4. Comparison and Discussion

In this section, the rigid body drop test and ice drop test results are compared and the KOSORI ice model is compared with the ice drop experiment.

4.1 Rigid body and ice drop experiment comparison

Figure 13 shows the results of the rigid body drop experiment and the finite element model force displacement. The finite element results correspond to the experimental results and indicate that the material model chosen for the plate is acceptable.

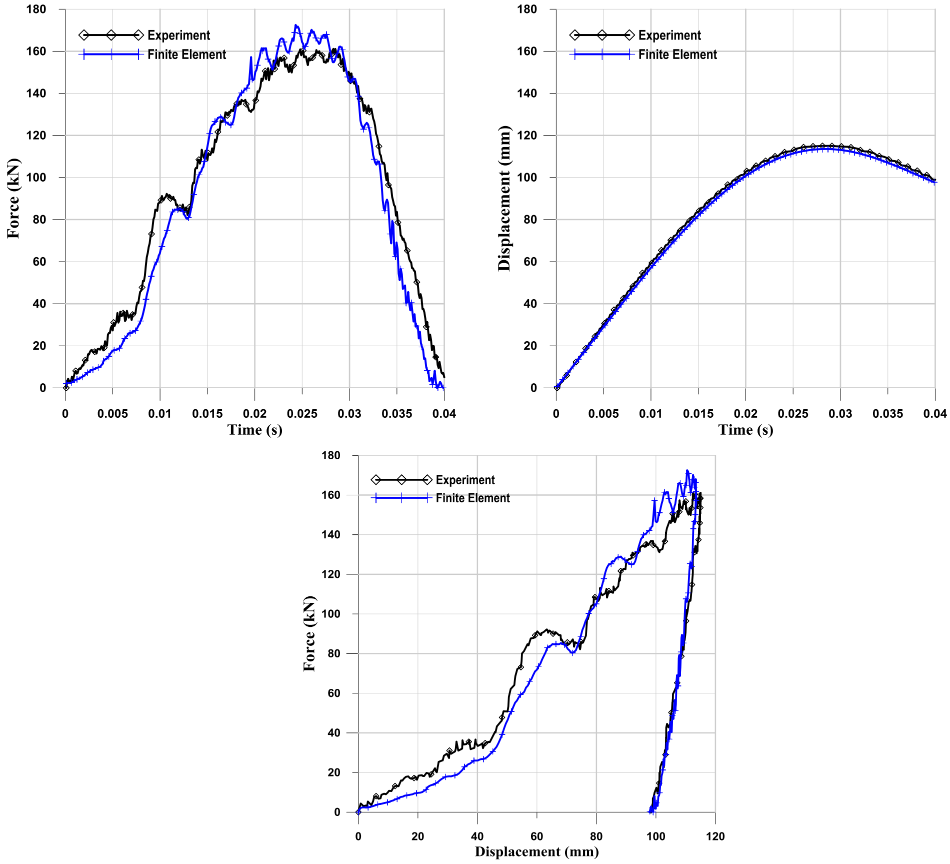
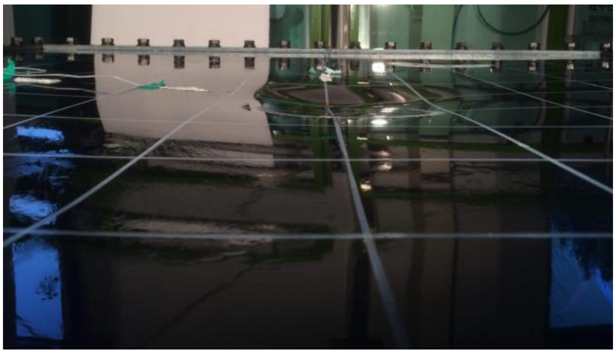
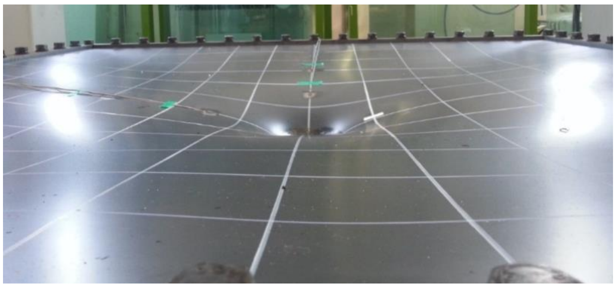


Figure 13 Comparison of the force-displacement relationships for the rigid body drop test and finite element analysis

Different results are obtained for the ice and rigid body drop experiments. Figure 14 shows the deformation of the plate after the experiments. Under similar conditions, the ice drop test created a 32 mm deflection in the steel plate, whereas the rigid body made a 98 mm deflection on the same plate.



(a) Ice drop test - Maximum deflection 32 mm



(b) Rigid drop test - Maximum deflection 98 mm

Figure 14 Steel plate deformation after the ice and rigid body drop tests

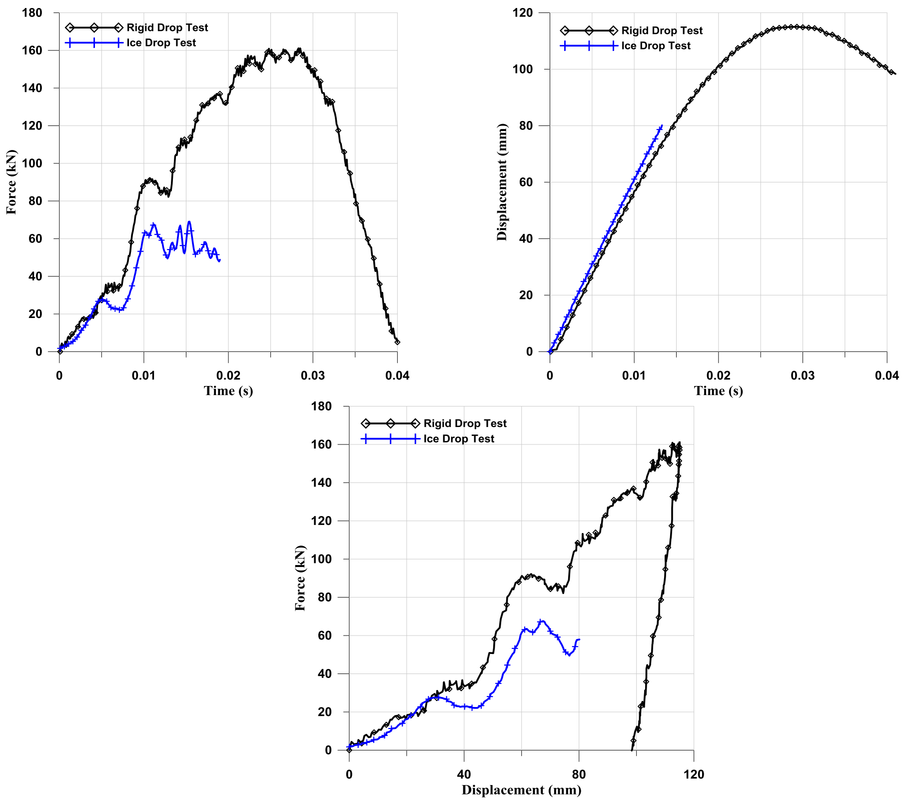


Figure 15 Comparison of the force and displacement changes in the rigid body and ice drop tests.

The load cell results also differ. Figure 15 shows the force-time relationships for both experiments. For the ice drop test, the load cell shows a maximum value of around 65 kN, whereas in the rigid body drop test, the load cell shows a maximum value of around 160 kN. As abovementioned, assuming the ice material is a rigid body gives very unrealistic responses.

4.2 Comparison of the KOSORI ice model and ice drop experiment

Figure 16 shows the force-displacement changes for the KOSORI ice model and the ice drop experiments. The results are very close to each other.

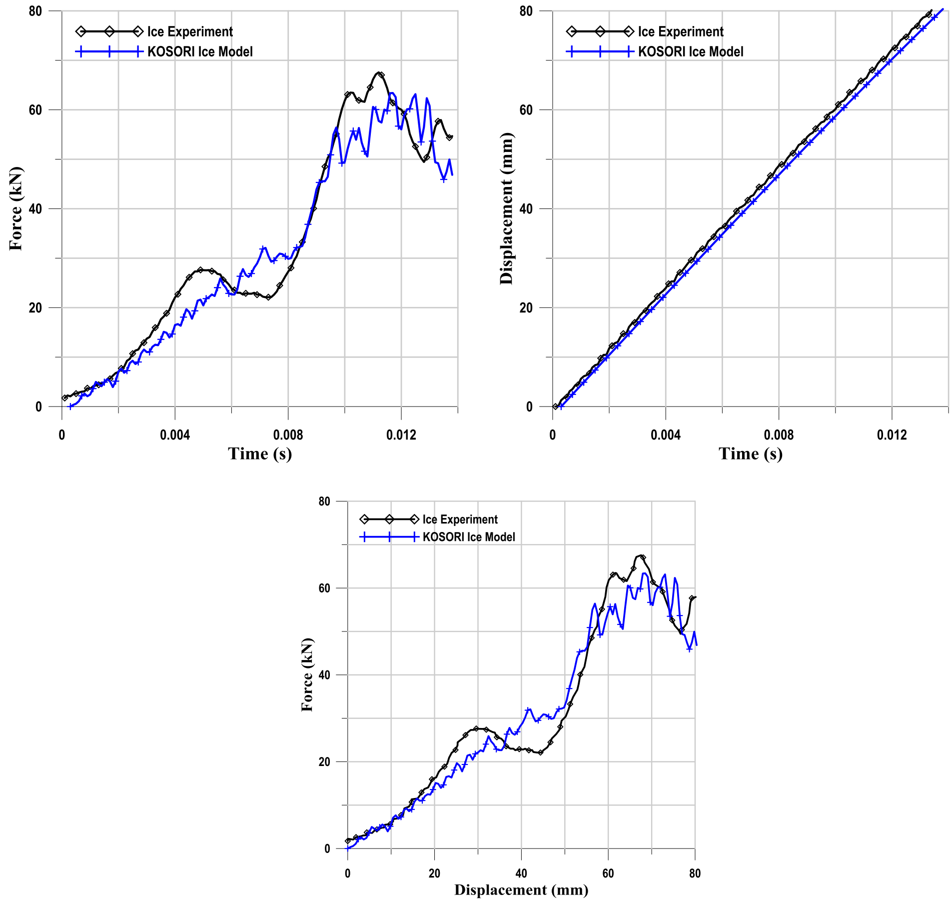


Figure 16 Force-displacement changes for the ice drop experiment and KOSORI model

Figure 17 shows the fracture propagation in the ice drop experiment from the high speed camera images and Figure 18 shows the fracture propagation according to the KOSORI ice model.

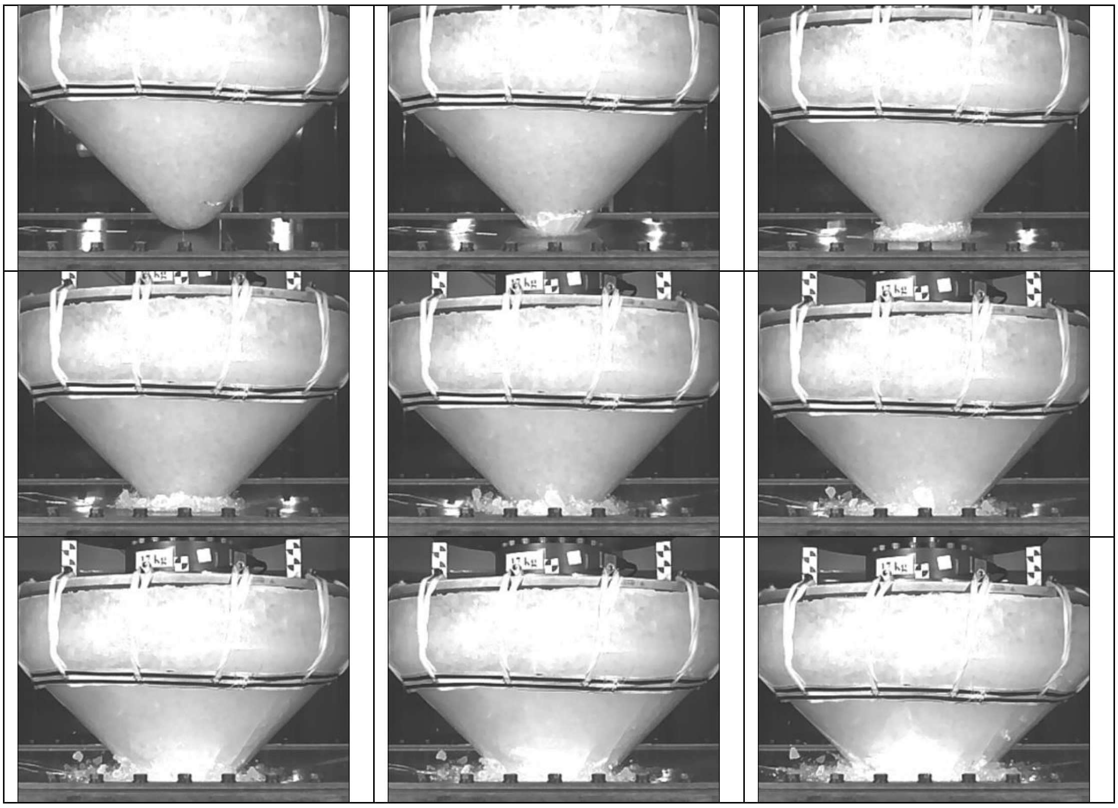


Figure 17 Ice fracture evaluation during the ice drop test using a high speed camera

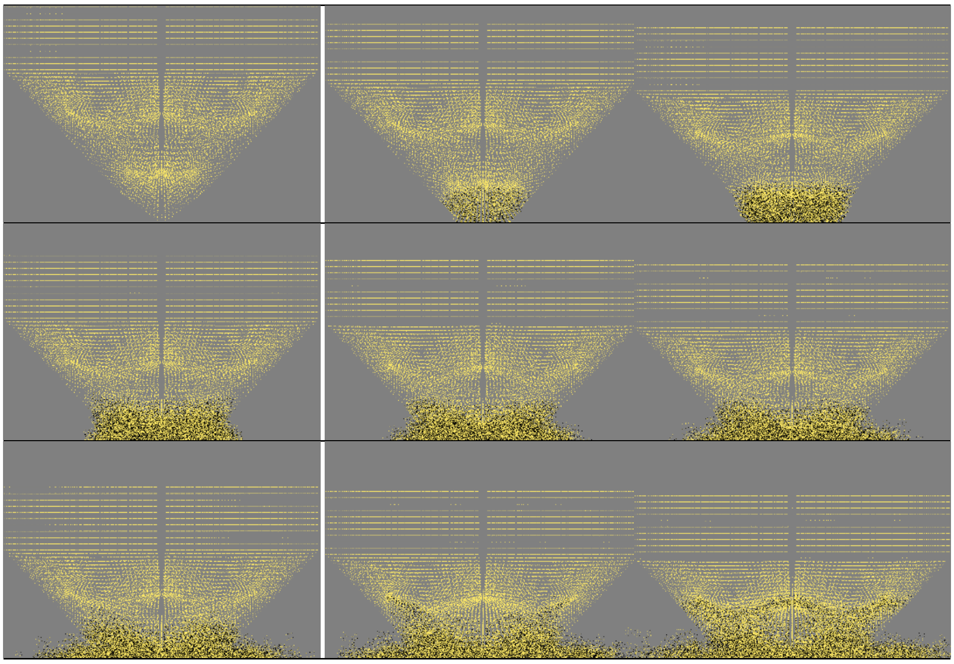


Figure 18 Ice fracture evaluation in the KOSORI ice model

The total deflection measured at the end of the experiment was 32 mm. In the numerical simulation, the deflection was 32.5 mm. Figure 19 shows the plate conditions at the end of the simulation and experiment.

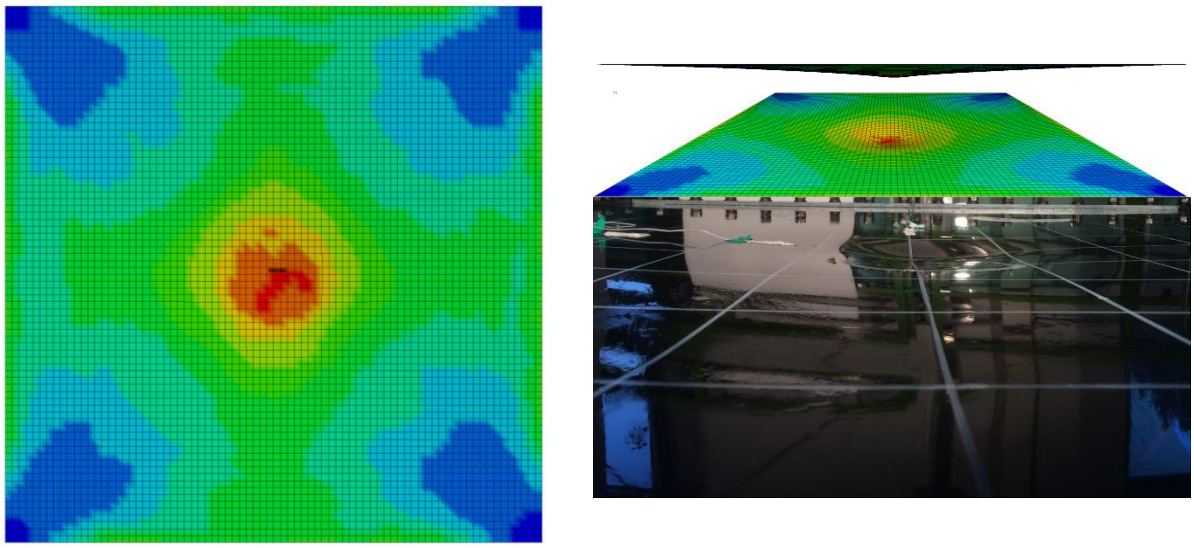


Figure 19 Comparison of the plate deflection in the experiment and the KOSORI model

5. Conclusions

The objective of this paper was to develop an advanced technology for computing the structural crashworthiness of a ship colliding with an ice-ridge. Some impact tests were conducted to obtain the material behaviour of the ice and steel. The responses of ice under the rigid assumption and real ice responses on steel plate were compared with the experimental results and the results were found to be quite different.

The results confirmed the need for a well-defined ice material model. The rigid impact tests were simulated in the finite element program using the suggested material model and the responses of the experiment and computer simulations were found to be similar. The results of the simulation in which the ice was defined by the KOSORI ice material model were then compared with those of the ice impact experiment, and the fracture propagation in the material and the responses of the steel materials were found to be comparable.

The KOSORI ice material model was also found to be capable of simulating the ice behaviour, which was comparable to the experimental results. Thus, this model provides an easy and economical way to accurately simulate the interaction between ice and steel structures.

Acknowledgements

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